Systems Engineering for Life Cycle of Complex Systems

All complex systems require systems engineering that integrates across the subsystems to meet mission requirements. This interdisciplinary field of engineering traditionally focuses on the development and organization of complex systems. However, NASA applied systems engineering throughout the life cycle of the Space Shuttle Program—from concept development, to production, to operation and retirement. It may be surprising to many that systems engineering is not only the technical integration of complex space systems; it also includes ground support and environmental considerations. Engineers require the aid of many tools to collect information, store data, and interpret interactions between shuttle systems. One of the shuttle's legacies was the success of its systems engineering. Not only did the shuttle do what it was supposed to do, it went well beyond meeting basic requirements.

This section is about systems engineering innovations, testing, approaches, and tools that NASA implemented for the shuttle. Companies that developed, built, and maintained major shuttle components are highlighted. As manufacturers, contractors, NASA, and industry employees and management came and went, the shuttle stayed the same during its lifetime, primarily because of its well-honed process controls. All of these systems engineering advances are a legacy for the International Space Station and for future space vehicles.

Systems Engineering During Development of the Shuttle

Systems engineering is a complex, multilevel process that involves deconstructing a customers' overall needs into functions that the system must satisfy. But even in ordinary situations, that's just the beginning. Functional requirements are then allocated to specific components in the system. Allocated functions are translated into performance requirements and combined with design constraints to form requirements that a design team must satisfy. Requirements are then synthesized by a team of engineers into one or more concepts, which are traded off against each other. These design concepts are expanded into preliminary and detailed designs interspersed with reviews. Specialists from many disciplines work as a team to obtain a solution that meets the needs and requirements. Selected designs are translated into manufacturing, planning, procurement, operations, and program completion documents and artifacts.

Systems engineering for the Space Shuttle presented an extraordinary situation. The shuttle was the most complex space vehicle for its time and, therefore, required the evolution of systems engineering with significantly advanced new tools and modeling techniques. Not only was the vehicle sophisticated, it required the expertise of many people. Four prime contractors and thousands of subcontractors and suppliers, spread across the United States, designed and built the major elements of the shuttle. The complexity of the element interfaces meant the integration of elements would present a major systems engineering challenge. One prime contractor was in charge of building the main engines, which were mounted inside the Orbiter. A different prime contractor built the Orbiter. A third prime contractor built the External Tanks, which contained the fuel for the main engines. And, a fourth prime contractor built the Solid Rocket Boosters. As problems occurred, they involved multiple NASA engineering organizations, industry partners, subject matter experts, universities, and other government agencies. NASA's ability to bring together a wide group of technical experts to focus on problems was extremely important. Thus, one legacy of the Space Shuttle was the success of its systems engineering. Not only did the shuttle do what it was supposed to do, it went well beyond meeting basic requirements.

A discussion of all the systems engineering models and new tools developed during the lifetime of the Space Shuttle Program would require volumes. All elements of the Space Shuttle Program had successes and failures. A few of the most notable successes and failures in systems engineering are discussed here.

Change and Uncertainty

Space Shuttle Main Engines

NASA recognized that advancements were needed in rocket engine technology to meet the design performance requirements of the shuttle. Thus, its main engine was the first contract awarded.

A high chamber pressure combined with the amplification effect of the staged combustion cycle made this engine a quantum leap in rocket engine technology for its time. The engine also had to meet the multiple interface requirements to the vehicle, extensive operation requirements, and several design criteria. A major challenge for systems engineering was

Intercommunication Comes of Age—The Digital Age

As the shuttle progressed, it became evident that the existing communication system could not meet the multi-flow and parallel processing requirements of the shuttle. A new system based on digital technology was proposed and Operational Intercommunication System-Digital was born, and is now in its third generation. This system provided unlimited conferencing on 512 communication channels and support for thousands of end users. The system used commercially available off-the-shelf components and custom-designed circuit boards.

Digital communication systems included, among other things, the voice communication system at Kennedy Space Center (KSC). The voice communication system needed to perform flawlessly 24/7, 365 days a year. This need was met by Operational Intercommunication System-Digital—a one-of-a-kind communication system conceived, designed, built, and operated by NASA engineers and a team of support contractors. The system was installed in every major processing facility, office building, and various labs around KSC. This widespread distribution allowed personnel working on specific tasks to communicate with one another, even in separate facilities.

Dominic Antonelli
Commander, US Navy.
Pilot on STS-119 (2009) and STS-132 (2010).

"At the end of the day, people comprise the system that ultimately propelled the Space Shuttle Program to its stellar place in history. The future of space travel will forever be indebted to the dedication, hard work, and ingenuity of the men and women, in centers across the country, who transformed the dream into a tangible reality and established a foundation that will inspire generations to come."

that all of these requirements and design criteria were interrelated.

In most complex systems, verification testing is performed at various stages of the buildup and design. NASA followed this practice on previous vehicles. In component-level tests, engineers find problems and solve them before moving to the next higher assembly level of testing. The main engine components, however, were very large. Test facilities that could facilitate and perform the component and higher assembly level tests did not exist. The valves alone required a relatively large specialized test facility. Plans to build such facilities had been developed, but there was not enough time to complete their construction and maintain the schedule. Therefore, the completed main engine became the test bed.

A concurrent engineering development philosophy associated with the shuttle forced the engine to be its own test bed. The engine test stands at Stennis Space Center in Mississippi were already in place, so NASA decided to assemble the engines and use them as the breadboard or facility to test the components. This was a risky scenario. The engine proved to be unforgiving. NASA lost 13 engines from catastrophic failures on the test stand before first flight. Each of these failures was a rich learning experience that significantly enabled the engineers to improve the engine's design. Still, at times it seemed the technical challenges were insurmountable.

Another philosophy that prevailed in the development of the main engines was "test, test, and test some more." Testing was key to the success of this shuttle component. Technicians conducted tests with cracked blades, rough bearings, and seals with built-in flaws to understand the limitations. By late 1979, as noted in a paper written by Robert Thompson, Space Shuttle manager at the time: "We have conducted 473 single engine tests and seven multiple engine tests with a cumulative total running time of 98 times mission duration and with 54 times mission duration at the engine rated power level. Significant engine test activities still remain and must be completed successfully before the first flight, but the maturity of this vital system is steadily improving."

The test, test, and test some more philosophy reduced risk, built robustness, and added system redundancy. Testing also allowed engineers to understand interactions of failures with other systems during the 30 years of the program. In all, the main engines were upgraded three times. These upgrades improved the engines' performance and reliability, reduced turnaround costs, and were well-planned system engineering efforts.

Throughout the life of the Space Shuttle Program—and through many technical challenges and requirement changes—the main engine not only performed, but was also a technological leap for spacecraft rocket engines.

Where Was Systems Engineering When the Shuttle Needed It Most?

Thermal Protection System

Early development problems with the Orbiter's Thermal Protection System probably could have been avoided had a systems engineering approach been implemented earlier and more effectively.

The Thermal Protection System of the Orbiter was supposed to provide for the thermal protection of the structure while maintaining structural integrity. The engineers did a magnificent job in designing tiles that accepted, stored, and dissipated the heat. They also created a system that maintained the aerodynamic configuration. However, early in the process, these engineers neglected to design a system that could accept the loads and retain the strength of the tiles. Furthermore, it was not until late in the Thermal Protection System development process that NASA discovered a major problem with the attachment of tiles to the Orbiter's aluminum skin surfaces.

In 1979, when Columbia—the first flight Orbiter—was being ferried from Dryden Flight Research Center in California to Kennedy Space Center in Florida on the back of the 747 Shuttle Carrier Aircraft, several tiles fell off. This incident focused NASA's attention on the tile attachment problem. The solution ultimately delayed the maiden flight of Columbia (Space Transportation System [STS]-1) by nearly 1½ years. The problem resided in the bond strength of the tiles, which was even lower than the overall low strength of the tile material. Tile load analyses kept showing increasing loads and lower margins on tile strength. This low bond strength was related to stress concentrations at the bondline interface between the tile and the strain isolation pad. Attachment of the tiles to the Orbiter's aluminum skin required that the strains from structural deflections be isolated from the tiles. In other words, the tiles could not be bonded directly to the Orbiter structure.

Strain isolation was accomplished with Nomex® felt pads bonded to the structure. In turn, the tiles bonded to the pads. Needling of the Nomex® pads through the thickness to control thickness resulted in straight through fibers ("stiff spots") that induced point loads in the bottom of the tiles. These point loads caused early localized failure of the tile material at the bondline. This did not meet design requirements.

After more than 1 year of intense, around-the-clock proof testing, bonding, removing, and re-bonding of tiles on the vehicle at Kennedy Space Center, tile densification proved to be the solution. Stress concentrations from the strain isolation pad were smoothed out and the full tile strength was regained by infusing the bottom of the tiles, prior to bonding, with a silica-based solution that filled the pores between tile fibers for a short distance into the bottom of the tile. This example demonstrates that a systems approach to the tile design, taking into consideration not only the thermal performance of the tile but also the structural integrity, would have allowed the tile attachment problem to be solved earlier in the design process.

The Importance of Organizational Structure

The structure of the Space Shuttle Program Systems Integration Office was a key element in the successful execution of systems engineering. It brought together all shuttle interfaces and technical issues. Design and performance issues were brought forward there. The office, which integrated all technical disciplines, also had a technical panel structure that worked the technical details from day to day.

The panels were composed of engineers from multiple NASA centers, prime contractors, and subcontractors. NASA also brought in technical experts when needed.

These panels varied in size. The frequency of discussions depended on the technical areas of responsibility and the difficulty of the problems encountered. The panels operated in an environment of healthy tension, allowing for needed technical interchange, questioning, and probing of technical issues. The technical panel structure has been recognized as a significant and an effective means to manage complex systems.

Initially, there were 44 formalized panels, subpanels, and working groups in the Space Shuttle Program Office.

Space Shuttle Systems Integration Program Structure

It takes a lot of people to integrate.

Systems Integration

Representatives

Systems Engineering

Prime	Support
Flight Performance Integration	Ancillary Hardware Requirements
Loads and Structural Dynamics	Commonality
Guidance, Navigation, and Control Integration	Quality Assurance
Integrated Avionics	Change Assessment
Integrated Prop. and Fluids	
Mechanical Systems	
Ascent Flight System Integration	
Thermal Design Integration	

Technical Integration

Prime	Support
Performance and Design Spec	Configuration Management
Flight Test Requirements	Change Integration
System Interfaces	Operational Requirements
Mass Properties	System Reviews
Systems/Ops Data Books	Major Ground Test Integration
Integrated Schematics	Network Interfaces
Materials and Processes	Element Reviews
Computer Systems Integration	Rockwell-Space Division Work Breakdown Structure
Integrated Systems Verification	

Test and Ground Operations

Prime	Support
Ground Systems Integration	Reliability
Maintainability	System Interfaces
Integrated Logistics	Safety
Integrated Test	Flight Test Requirements
Ground Support Equipment Requirements and Analysis	Systems Analysis and Design
Payload Integration for Design, Development, Test, and Evaluation	System Requirements

- Simulation Planning Panel
- Crew Safety Panel
- Configuration Management Panel
- Ground Interface Control Board
- Crew Procedures Control Board
- Information Management Systems Panel
- Payloads Interface Panel
- Program Information Coordination and Review Service Working Group
- Systems Integration Reviews
- Management Information Center Integration Panel
- Performance Management Panel
- Integrated Entry Performance Panel
- Crew Related Government Furnished Equipment Configuration Control Board
- Flight Test Program Panel
- Electromagnetic Effects Panel
- Ascent Performance Panel
- Abort Performance Panel
- Separation Performance Panel
- Aerothermodynamics Performance Panel
- Aerodynamic Performance Panel
- Main Propulsion Systems Panel
- Pogo Integration Panel
- Loads and Structural Dynamics Panel
- Ground Vibration Test Panel
- Spacecraft Mechanisms Panel
- Shuttle Vehicle Attachment and Separation Subpanel
- Payloads Docking, Retention, and Deployment Subpanel
- Landing Systems and Facilities Subpanel
- Shuttle Training Aircraft Review Board
- Communications and Data Systems Integration Panel
- Functional Requirements Subpanel
- Vehicle Communications Interface Subpanel
- Ground-Based Data Systems Subpanel
- Science and Engineering Data Processing Subpanel
- Flight Operations Panel
- Operations Integration Reviews
- Computer Systems Hardware/Software Integration Reviews
- Training Simulator Control Panel
- Ascent Flight Control/Structural Integration Panel
- On-Orbit Guidance and Control Panel
- Entry Guidance and Control Panel
- Approach and Landing Test Guidance and Control Panel
- Guidance and Navigation Systems Panel
- Safety, Reliability, and Quality Assurance Management Panel

The structure of the Space Shuttle Program was instrumental to its success. The panels listed on the right debated technical issues and reached technical decisions. These panels influenced multiple subsystems and were integrated by the Systems Integration Office.

However, because of the complexity, by 1977 the number had grown to 53 panels, subpanels, and working groups. These critical reviews provided guidance to maintain effective and productive technical decisions during the shuttle development phase. Also during this phase of the program, NASA established the definition and verification of the interfaces and associated documentation, including hazard analysis and configuration control.

Biggest Asset—People Working Together

Owen Morris, manager of the Systems Integration Office from 1974 to 1980, was an effective and a respected manager. When asked to describe the biggest challenge of that position, Owen answered, "People. Of course, all the people involved had their own responsibilities for their part of the program, and trying to get the overall program put together in the most efficient manner involved people frequently giving up part of their capability, part of their prerogative, to help a different part of the program, solve a problem, and do it in a manner that was better for everyone except them. And, that's a little difficult to convince people to do that. So, working with people, working with organizations, and getting them to work together in a harmonious manner was probably the most difficult part of that."

The challenge of getting people to work together successfully has been an enduring one. NASA stepped up to multiple challenges, including that of having various people and organizations working together toward a common goal. By working together, the space agency engineered many successes that will benefit future generations.

Restoring Integration and Systems Thinking in a Midlife Program

Aviation lore says that, during World War II, a heavily overworked crew chief confronted an aircraft full of battle damage and complained, "That's not an airplane, that's a bunch of parts flying in loose formation."

One of the greatest challenges during system development is transforming parts into a fully integrated vehicle. Glenn Bugos' book titled *Engineering the F-4 Phantom II* is subtitled *Parts into Systems* in recognition of this challenge. NASA also long realized this. In the standard NASA cost model for space systems, the agency planned that 25% of a program's development effort would go into systems engineering and integration. Efforts made during the initial development of the shuttle to ensure its integrated performance led to a successful and an enduring design.

NASA Learns an Expensive Lesson

NASA's experience in human spacecraft prior to the shuttle was with relatively short-lived systems. The agency developed four generations of human spacecraft—Mercury, Gemini, Apollo, and Skylab—in fewer than 15 years. Designers and project managers intuitively anticipated rapid replacement of human space systems because, at the time of shuttle development, they had no experience to the contrary. The initial design parameters for the Orbiter included 100 missions per Orbiter in 10 years. During the design phase, NASA did not plan for the 30-year operational life the shuttle actually flew.

The space agency, therefore, had no experience regarding the role of systems engineering and integration during the extended operational part of a system life cycle. Given the cost of a strong systems engineering and integration function, this was a topic of significant debate within NASA, particularly as budgets were reduced. As late as 1990—9 years after the shuttle's first flight—the systems engineering and integration effort was approximately \$160 million per year, or approximately 6.4% of the \$2.5 billion shuttle annual budget. Starting in 1992, to meet reduced operating budgets, this level of resource came under scrutiny. It was argued that, given major development of the shuttle system was complete, all system changes were under tight configuration control and all elements understood their interfaces to other elements, the same level of systems engineering and integration was no longer required. The effort was reduced to 2.2% of the shuttle annual budget in 1992. Occurrences of in-flight anomalies were decreasing during this period, thereby lending to the belief that the proper amount of integration was taking place.

This seemed to be a highly efficient approach to the problem until the loss of Columbia in 2003. In retrospect, the Columbia Accident Investigation Board determined there were clear indicators that the program was slowly losing the necessary degree of systems engineering and integration prior to the loss of Columbia. Critical integration documentation no longer reflected the vehicle configuration being flown. Furthermore, the occurrence of integrated anomalies was increasing over the years.

Crucial Role of Systems Engineering

Known Changes

Change was constantly occurring in the shuttle systems. Changes with known effects required a large and expensive integrated engineering effort but were usually the easiest to deal with. For example, when NASA upgraded the Space Shuttle Main Engines to a more-powerful configuration, a number of changes occurred in terms of avionics, electrical, and thrust performance. These changes had to be accommodated by the other parts of the system.

Known changes with unknown effects were more difficult to deal with. For example, as a cost-reduction effort, NASA decided not to replace the connectors on the Orbiter umbilicals after every flight. At the time, NASA did not know that the Solid Rocket Booster exhaust and salt-spray environment of the pad created corrosion on the connectors. This corrosion would eventually interrupt safety-critical circuits. On Space Transportation System (STS)-112 (2002), half the critical pyrotechnic systems, which release the shuttle from the launch pad, did not work. Because the systems had redundancy, the flight launched successfully.

Unknown Changes—Manufacturing Specification

There were many sources of unknown change during the Space Shuttle Program. First, the external environment was continually changing. For example, the electromagnetic environment changed as radio-frequency sources appeared and disappeared in terrain over which the shuttle flew. These sources could influence the performance of shuttle systems.

Second, the characteristics of new production runs of materials such as adhesives, metals, and electronic components changed over time. It was impossible to fully specify all characteristics of all materials on a large system. Changes in assembly tooling or operators could have resulted in a product with slightly different characteristics. For instance, major problems with fuel quality circuits caused launch delays for flights after the Columbia accident. The circuits were intended to identify a low fuel level and initiate engine shutdown, thus preventing a probable engine catastrophe. These circuit failures were random. While these anomalies remained unexplained, the circuit failures seemed to stop after improvements were made to the engine cutoff sensors. However, following another failure on STS-122 (2008), the problem was isolated to an electrical connector on the hydrogen tank and was determined to be an open circuit at the electrical connector's pin-to-socket interface. The increased failure rate was likely caused by a subtle change to the socket design by the vendor, combined with material aging within the connector assembly. The connector was redesigned, requiring soldering the sockets directly to the pins.

Solution—Systems Engineering

The only way to deal with known and unknown change was to have a significant effort in systems engineering and integration that monitored integrated flight performance and was attuned to the issues that could impact a system. One of the best approaches for maintaining this vigilance was comparing in-flight anomalies to established analyses of hazards to the integrated system. These integrated hazard analyses were produced at the start of the program but had not been updated at the time of the Columbia accident to reflect the present vehicle configuration. Further, the in-flight anomaly process was not tied to these analyses. In the period before Return to Flight, the systems engineering and integration organization tried to fix these analyses but determined the analyses were so badly out of date that they had to be completely redone. Thus, systems engineering and integration replaced 42 integrated hazards with 35 new analyses that used fault-tree techniques to determine potential causes of hazards to the integrated system. These analyses were also tied into a revamped in-flight anomaly process. Any problem occurring in flight that could cause a hazard to the integrated system required resolution prior to the next flight.

Preparing for Return to Flight After the Columbia Accident

When internal NASA evaluations and the Columbia Accident Investigation Board determined that shuttle systems engineering and integration would need to be rebuilt, NASA immediately recognized that systems engineering and integration could not be rebuilt to 1992 levels. There were simply not enough available, qualified systems engineers who were familiar with the shuttle configuration. Further, it was unlikely that NASA could afford to maintain the necessary level of staffing. NASA accomplished a modest increase of about 300 engineers by selective hiring. Also, NASA worked with the Aerospace Corporation (California), along with establishing agreements with other NASA centers, such as integration personnel at Marshall Space Flight Center and Kennedy Space Center. This returned systems engineering and integration activities to 1995 levels. More impressive was the way in which these resources were deployed.

The most immediate job for systems engineering and integration during this

Left photo: Ames Research Center wind tunnel test.
Right photo: Aerothermal test at Calspan-University of Buffalo Research Center.

period was determining design environments for all redesigns mandated by the Columbia Accident Investigation Board. The standard techniques for establishing design environments prior to this effort involved constructing environment changes to the basic environments by making conservative calculations based on the nature of the change.

A large number of configuration changes over the years resulted in an accumulation of conservative design environments. However, this cumulative approach was the only basis for estimating the environments. A new baseline effort would have required extensive calculations and ground tests. For the Return to Flight effort, systems engineering and integration decided to re-baseline the critical design environments to eliminate non-credible results. Fortunately, technology had advanced significantly since the original baseline environments were constructed in the 1970s. These advances enabled greater accuracy in less time.

The shuttle aerodynamics model was refurbished to the latest configuration for aerodynamics and aerodynamic loads. Shuttle wind tunnel tests were completed at Ames Research Center in California and the Arnold Engineering Development Center in Tennessee. Engineers employed new techniques, such as pressure-sensitive paint and laser velocimetry in addition to more advanced pressure and force instrumentation. The purpose of these tests was to validate computational fluid dynamics models because design modifications were evolving as the design environments were being generated. Thus, continued wind tunnel tests could not generate the final design environments. Validated computational fluid dynamics models were necessary to generate such environments for the remainder of the Space Shuttle Program to avoid the accumulation of conservative environments.

Engineers performed similar tests using the aerothermal model at the Calspan-University of Buffalo Research Center (New York) shock tunnel. Engineers used a combination of computational fluid dynamics and other engineering methods to generate an updated thermal database.

Another major task for systems engineering and integration was to understand the debris transport problem. A 0.76-kg (1.67-pound) piece of foam debris was liberated from the External Tank. This foam debris was responsible for the damage that caused the Columbia accident. Systems engineering and integration enabled engineers to identify the transport paths of debris to the shuttle to determine the hazard level of each debris item as well as determine the impact velocities that the structure would have to withstand. When analysis or testing revealed the elements could not withstand impact, systems engineering and integration worked with the debris-generating element to better understand the mechanisms, refine the estimated impact conditions, and determine whether debris-reduction redesign activities were sufficient to eliminate or reduce the risk. To understand debris transport, NASA modeled the flow fields with computational fluid dynamics and flight simulation models. Fortunately, NASA had entered into an agreement, post-Columbia, to create the world's largest supercomputer at Ames Research Center. This 10,240-element supercomputer came on line in time to perform extensive computational fluid dynamics and simulation analysis of debris transport.

Debris Transport During Launch Remained a Potential Hazard

NASA cataloged both the size and the shape of the debris population as well as the debris aerodynamics over a wide speed range. A large part of this

NASA validated computational fluid dynamics and flight simulation models of the foam debris in flight tests using the Dryden Flight Research Center (California) F-15B Research test bed aircraft. In these tests, debris fell from foam panels at simulated shuttle flight conditions. High-speed video cameras captured the initial flight of the foam divots.

effort involved modeling the flight characteristics of foam divots that came off of the tank. NASA first addressed this problem by firing small plastic models of foam divot shapes at the NASA Ames Research Center, California, ballistic range. When these results correlated well with computational fluid dynamics, the agency conducted more extensive tests. Engineers tested flight characteristics of foam debris in the Calspan-University of Buffalo Research Center tunnel and Dryden Flight Research Center, California. Results showed that foam would stay intact at speeds up to Mach 4 and, therefore, remain a potential hazard.

Other Return to Flight Activities

Two other major tasks were part of the systems engineering and integration Return to Flight effort. The first task involved integrated test planning to ensure that the system design was recertified for flight. The second task was to install additional instrumentation and imagery acquisition equipment to validate the performance of system design changes.

The diversity of integrated system testing was remarkable. Integrated tests included the first-ever electromagnetic interference tests run on the shuttle system. NASA ran a test to determine the effects of the crawler transporter on the vibration/fatigue of shuttle structures. This effort required construction of improved integrated structural models. First performed on a limited scale during the Return to Flight period, this effort expanded under Marshall Space Flight Center leadership. The integrated test effort also included two full-up tanking tests of the shuttle system. In addition to validating the performance of the new foam system on the tank, these tanking tests discovered two major problems in the shuttle: failures of the propellant pressurization system and problems with the engine cutoff sensors.

The instrumentation added to the shuttle system as part of the systems engineering and integration effort was also diverse. NASA added instrumentation to the External Tank to understand the vibration and loads on major components attached to the skin. These data proved vital after Return to Flight assessment because a loss of foam associated with these components required additional modification. This instrumentation gave the program the confidence to make these modifications. NASA also added instrumentation to help them understand over-pressure effects on the shuttle due to ignition transients of the Space Shuttle Main Engine and motion of the Orbiter-ground system umbilicals. The agency added ground-based radar and video imaging equipment to provide greater visibility into the debris environment and validate design modifications.

Integration Becomes the Standard

NASA learned some difficult yet valuable lessons about the importance of systems engineering and integration over the course of the Space Shuttle Program—especially in the years following the loss of Columbia. The lack of systems engineering and integration was a contributing cause to the accident. The shuttle had become "a collection of parts flying in loose formation." It took a major engineering effort over a 2-year period to reestablish the proper amount of integration. This effort significantly improved the shuttle system and laid the groundwork and understanding necessary for the successful flights that followed.

Electromagnetic Compatibility for the Space Shuttle

Electromagnetic compatibility is extremely complex and far reaching. It affects all major vehicle engineering disciplines involving multiple systems and subsystems and the interactions between them. By definition, electromagnetic compatibility is the capability of electrical and electronic systems, equipment, and devices to operate in their intended electromagnetic environment within a defined margin of safety, and at design levels of performance. But, that is just the beginning. This must be accomplished without causing unacceptable degradation as a result of any conducted or radiated electromagnetic energy that interrupts, obstructs, or otherwise limits the effective performance of telecommunications or other electrical and electronic equipment.

Design and Verification Requirements—A Learning Process

In 1973—when NASA was first defining the shuttle systems—military models offered the best available means of providing control of the system design leading to acceptable levels of electromagnetic compatibility. Previous requirements for Mercury, Gemini, and Apollo were cut from the same cloth, but none of those programs had a vehicle that could compare to the shuttle in terms of size and complexity.

Admittedly, these comprehensive requirements addressed a multiplicity of concerns. These included: subsystem criticality; degradation criteria; interference and susceptibility control;

wiring and cable design and installation; electrical power; electrical bonding and grounding; control of static electricity and its effects; electromagnetic hazards to personnel, explosives, and ordnance; and definition of, and design for, the external electromagnetic environment.

Detailed design and verification requirements for protection from the damaging effects of lightning were also included and developed independently by NASA. These shuttle lightning requirements became the foundation for a plethora of military and commercial aerospace requirements, culminating in a detailed series of Society of Automotive Engineers documents universally employed on an international basis.

A Custom Fit Was Needed

Unfortunately, without a solid basis for the tailoring of requirements, shuttle electromagnetic compatibility engineers chose to levy the baseline requirements with virtually no change from previous Apollo efforts. Although this was a prudent and conservative approach, it led to misinterpretation and misapplication of many requirements to the shuttle. As a result, NASA granted an unacceptably large number of waivers for failure to comply with the requirements. The problem continued to grow until 2000, at which time NASA made a major effort to completely review and revise the electromagnetic compatibility requirements and compliance approach. This effort eliminated or tailored requirements so that the content was directly and unequivocally applicable to the shuttle. This effort also allowed for a systematic and detailed revisitation of previously granted waivers against the backdrop of the new requirements' definitions.

Making Necessary Adjustments…and Succeeding

Original requirements and new requirements were tabulated together to facilitate direct comparison. For each set of requirements, NASA needed to examine several characteristics, including frequency range, measurement circuit configuration, test equipment application, and the measured parameter limits. As an example, certain conducted emissions requirements in the original set of requirements measured noise currents flowing on power lines whereas the equivalent new requirements measured noise voltages on the same power lines. To compare limits, it was necessary to convert the current limits to voltage limits using the linear relationship between voltage, current, and circuit impedance. In other cases, frequency bandwidths used for testing were different, so NASA had to adjust the limits to account for the bandwidth differences.

In all, NASA engineers were able to work through the complexity of electromagnetic compatibility—to follow all of the threads inherent in the vehicle's multiple systems and subsystems—and find a way to tailor the requirements to accommodate the shuttle.

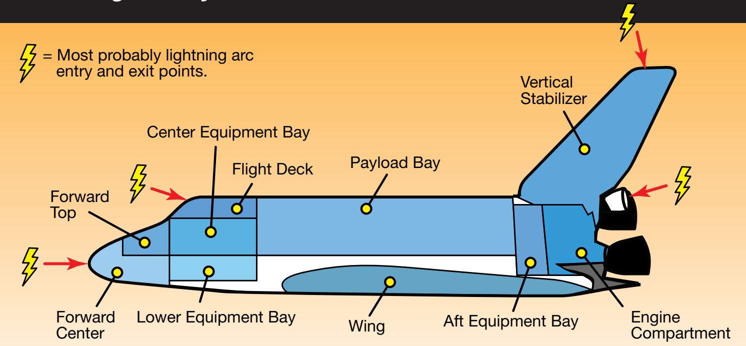
Process Control

The design and fabrication of the Space Shuttle's main components took place in the early 1970s while Richard Nixon was president. The Space Shuttle was assembled from more than 2.5 million parts that had to perform per design with very little margin of error. NASA constantly analyzed and refurbished flight systems and their components to ensure performance. The success of the Space Shuttle Program was due in great part to diligent process control efforts by manufacturing teams, contractors, and civil service engineers who carefully maintained flight hardware.

Five Key Elements Ensure Successful Process Control

Process control consists of the systems and tools used to ensure that processes are well-defined, perform correctly, and are maintained such that the completed product conforms to requirements. Process control managed risk to ensure safety and reliability in a complex system. Strict process control practices helped prevent deviations that could have caused or contributed to incidents, accidents, mishaps, nonconformances, and in-flight

Electromagnetically Shielded Zones Within the Orbiter Structure



anomalies. As defined by NASA, the five key elements of a process are: people, methods/instructions, materials, equipment, and environment. It has been long understood that qualified, conscientious people are the heart of any successful operation. High-quality process control efforts require skilled, detail-oriented individuals who understand and respect the importance of process and change control. The methods or instructions of a process, often called "specifications" or "requirements," are those documented techniques used to define and perform a specific process. The term "equipment" refers to the tools, fixtures, and facilities required to make products that meet specifications and requirements while "materials" refers to both product and process materials used to manufacture and test products. Finally, the environmental conditions required to properly manufacture and test products must also be maintained to established standards to ensure safety and reliability.

Solid Engineering Design—A Fundamental Requirement

A clear understanding of the engineering design is fundamental when changes occur later in a program's life. Thousands of configuration changes occurred within the Space Shuttle Program. These changes could not have been made safely without proper process controls that included a formal configuration control system. This

Alliant Techsystems, Inc. and United Space Alliance

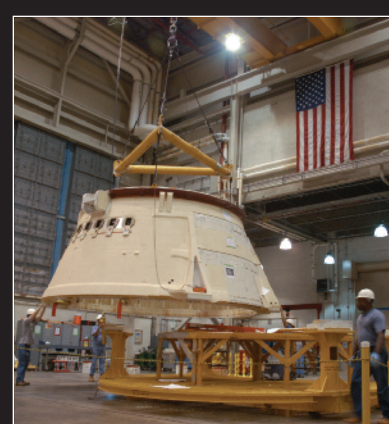
The signature twin reusable solid rocket motors of the Space Shuttle carried the fingerprints of thousands of people who designed, manufactured, tested, and evaluated the performance of these workhorse motors since 1982. The manufacturing facility in Promotory, Utah, is now owned and operated by Alliant Techsystems, Inc. (ATK). Originally developed to manufacture and test large-scale rocket motors for intercontinental ballistic missiles, the site provided 72% of the liftoff thrust to loft each shuttle beyond Earth's bounds.

Technicians process the solid rocket motor case segments at the ATK case lining facility in Utah.

The Assembly Refurbishment Facility complex—managed and operated by United Space Alliance (USA), headquartered in Houston, Texas—is located at Kennedy Space Center, Florida. The complex began operations in 1986 and was the primary integration and checkout facility for boosters. Refurbished and new hardware were assembled and submitted to rigorous testing to assure the assemblies were ready for human-rated flight. The facility was equipped to handle assembly, testing, and troubleshooting of thrust vector control systems, avionics, and recovery systems for the Space Shuttle Program.

Solid Rocket Booster case preparation.

Propellant mixing.



Solid Rocket Booster aft skirt processing at the Assembly and Refurbishment Facility at Kennedy Space Center.

system involved the use of review boards, material review analyses, and tool controls.

A Team Effort

Hardware for the Space Shuttle Program was manufactured by a broad supplier base using a variety of processes. If these processes were not controlled, a deterioration of the end product could have occurred, thereby increasing risk. In essence, NASA depended on the process controls at over 3,000 flight hardware suppliers' facilities across the United States. Any subtle changes or deviations from any established processes could have negatively affected the outcome.

Think of the thousands of vendors and processes that might have affected manufacturing—from material pedigree to the material of gloves worn by a technician. All of these nuances affected the outcome of the product. Coordination and communication between NASA and its manufacturers were critical in this complicated web of hardware suppliers. The Space Shuttle was only as strong as its weakest link.

Strong process controls resulted in highly predictable processes. Built-in tests were critical because many flight components/systems could not be tested prior to their actual use in flight. For example, Thermal Protection Systems, pyrotechnics, and solid rocket motors could only be tested at the manufacturer's facilities before they were installed aboard the shuttle. This fact demonstrated once again that NASA was highly dependent on the integrity of its hardware suppliers to follow the tried and true "recipe" of requirements, materials, people, and processes to yield predictable and reliable components.

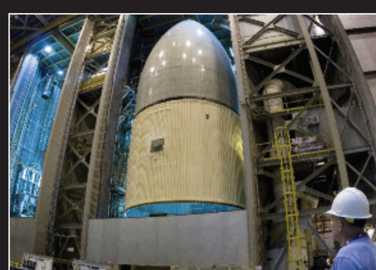
Michoud Assembly Facility

By the end of the Space Shuttle Program, NASA's Michoud Assembly Facility—located near New Orleans, Louisiana, and managed by Marshall Space Flight Center in Huntsville, Alabama—delivered 134 External Tanks (ETs) for flight. Two additional tanks were built but not scheduled to fly, and three assemblies were delivered for major tests, resulting in a total of 139 tanks. As one of the world's largest manufacturing plants, Michoud's main production building measured 17 hectares (43 acres) under one roof, including a 61-m (200-ft) vertical assembly building, and a port that permitted transportation of ETs via oceangoing barges and towing vessels to Kennedy Space Center in Florida.

ETs were produced at Michoud by prime contractor Lockheed Martin (headquartered in Bethesda, Maryland) over a 37-year period. The contractor procured parts and materials from hundreds of subcontractors across the country. In full production, 12 tanks were in various phases of production across the facility—each tank requiring approximately 3 years to complete. Each ET included over 0.8 km (0.5 miles) of welds, thousands of rivets and bolts, redundant inspections within each process, and sophisticated pressure and electrical testing.

Throughout the history of the program, Michoud continually improved the processing, materials, and components of ETs. Improvements included the introduction of a stronger, lighter aluminum-lithium alloy—which saved over 2.7 metric tons (3 tons) of weight—and transitioning to virtually defect-free friction stir welding. Additionally, Michoud developed thermal protection foam spray systems and process controls that reduced weight and minimized foam loss during the extreme environments of flight.

Liquid oxygen tank.



Liquid oxygen tank and intertank in a checkout cell.

Liquid hydrogen tank showing slosh and vortex baffle inside.

External Tank processing.

Processes Continue Well Beyond Flight

Because shuttles were reusable vehicles, process control was also vital to refurbishment and postflight evaluation efforts. After each flight, NASA closely monitored the entire vehicle to evaluate factors such as heat exposure, aging effects, flight loads, shock loads, saltwater intrusion, and other similar environmental impacts. For example, did you know that each heat tile that protected the underbelly of the vehicle from the extreme heat of re-entry into Earth's atmosphere was numbered and checked following each flight? Tiles that did not pass inspection were either repaired or replaced. This effort was a major undertaking since there were 23,000 thermal protection tiles.

Postflight recovery and inspections were an important part of process control. For example, NASA recovered the Solid Rocket Boosters, which separated from the vehicle during launch and splashdown in the Atlantic Ocean, and brought them back to Kennedy Space Center in Florida where they were examined and inspected. These standardized forensic inspections provided valuable data that determined whether the booster system operated within its requirements and specifications. Data collected by the manufacturer represented the single most important feedback process since this system had to function as intended every time without the ability to pretest.

Best Practices Are Standard Practice

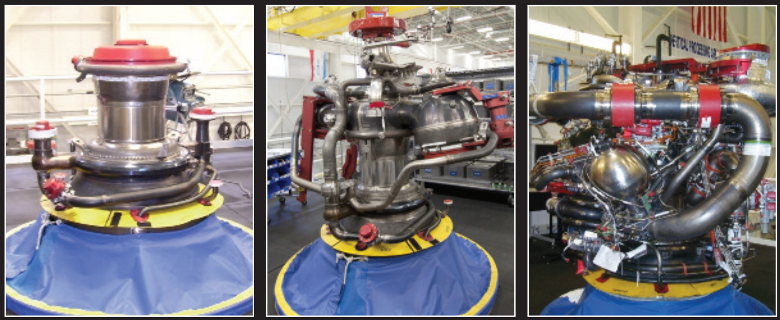
Each of NASA's manufacturers and suppliers had unique systems for process control that guaranteed the integrity of the shuttle's hardware.

Pratt & Whitney Rocketdyne Manufacturing

The Space Shuttle Main Engine required manufacturing and maintenance across the entire United States. Pratt & Whitney Rocketdyne (Canoga Park, California), under contract to NASA, developed the main engine, which successfully met the challenges of reusability, high performance, and human-rated reliability. With every launch, the team continued to make improvements to render it safer and more reliable.

High-pressure fuel turbopump recycling.

The Pratt & Whitney Rocketdyne facility at the West Palm Beach, Florida, campus designed and assembled the critical high-pressure turbomachinery for the shuttle. The high pressures generated by these components allowed the main engine to attain its extremely high efficiency. At the main facility in Canoga Park, California, the company fabricated and assembled the remaining major components. The factory included special plating tanks for making the main combustion chamber (the key components to attain high thrust with the associated high heat transfer requirements), powerhead (the complex structural heart of the engine), and nozzle (another key complex component able to withstand temperatures of 3,300°C [6,000°F] degrees during operation). In addition, the company employed personnel in Huntsville, Alabama, and Stennis Space Center in Mississippi. The Huntsville team created and tested critical software. The Stennis team performed testing and checkout of engines and engine components before delivery to the launch site. Finally, at Kennedy Space Center in Florida, Pratt & Whitney Rocketdyne personnel performed all the hands-on work required to support launch, landing, and turnaround activities.

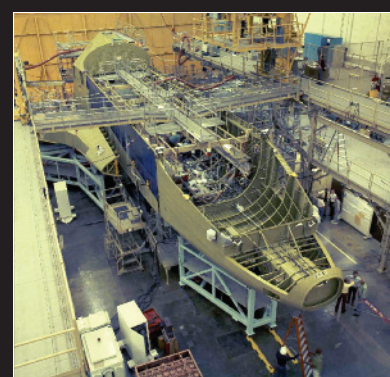


Space Shuttle Main Engine assembly.

Rockwell International and The Boeing Company

Rockwell of Downey, California (now Boeing) executed the Orbiter design, development, test, and evaluation contract, the production contract, and the system integration contract for the mated shuttle vehicle. Engineers were the primary producers of specifications, vehicle loads/environments, analysis, drawing release, certification/qualification testing, and certification documentation. Engineers performed key system-level integration and testing for many Orbiter subsystems including software, avionics hardware, flight controls/hydraulics, and thermal protection. At this same location, technicians manufactured the crew module, forward fuselage, and aft fuselage, which were integrated into the Orbiter at the Boeing facility in Palmdale, California.

Boeing engineers, technicians, and support personnel assembled and tested all six Space Shuttle Orbiter vehicles. The first shuttle vehicle, Enterprise, was delivered in January 1977. Being a non-orbital vehicle, it was used for fit checks, support equipment procedures, and the Approach and Landing Test Program conducted at Dryden Flight Research Center on the Edwards Air Force Base runway in California beginning in 1977. Columbia, the first space-rated Orbiter, was delivered in the spring of 1979 and later flew the Space Shuttle Program's maiden voyage in April 1981. Challenger was rolled out in 1982, followed by Discovery in 1983 and Atlantis in 1985. The newest shuttle, Endeavour, was authorized following the loss of Challenger in 1986 and was delivered in April 1991. From 1985 to 2001, engineers performed eight major modifications on the Orbiter fleet.

Orbiter assembly.

The communication and establishment of specific best practices as standards helped the program improve safety and reliability over the years. The following standards were the minimum process control requirements for all contractors within the Space Shuttle Program:

- Detect and eliminate process variability and uncoordinated changes.
- Eliminate creep—or changes that occur over time—through process controls and audits.
- Understand and reduce process risks.
- Identify key design and manufacturing characteristics and share lessons learned that relate to the processes.
- Be personally accountable and perform to written procedures.
- Promote process control awareness.
- Identify and evaluate changes to equipment and environment.
- Capture and maintain process knowledge and skills.

NASA witnessed a significant evolution in their overall process control measures during the shuttle period. This lengthy evolution of process control, a continuous effort on the part of both NASA and its contractors, included multiple initiatives such as:

- establishing reliable processes
- monitoring processes
- reinforcing the process-control philosophy or "culture"
- maintaining healthy systems

Establishing reliable processes included open communications (during and after the design process) among numerous review boards and change boards whose decisions dictated process-control measures. Monitoring processes involved postflight inspections, safety management systems, chemical fingerprinting, witness panels, and other monitoring procedures. Process control also referred to relatively new programs like the "Stamp and Signature Warranty" Program where annual audits were performed to verify the integrity of products/components for the shuttle era. Finally, maintaining healthy systems focused on sustaining engineering where design or operating changes were made or corrective actions were taken to enhance the overall "health" of the program.

An Enduring Success

Although NASA's process control measures have always been rigorous, additional enhancements for improved communication and information-sharing between shuttle prime contractors and suppliers created highly restrictive, world-class standards for process control across the program. Many of these communication enhancements were attainable simply because of advances in technology. The computer, for example, with its increased power and capabilities, provided faster and better documentation, communication, data tracking, archiving, lot number tracking, configuration control, and data storage. As manufacturers, contractors, and other businesses came and went—and as employees, managers, and directors came and went—the program stayed the same over its lifetime and continued to operate successfully primarily because of its well-honed process-control measures.

The Case of the Chloride Sponges

Let's look at "The Case of the Chloride Sponges" to further demonstrate the importance of process control and the complexities of maintaining the Space Shuttle fleet. Postflight maintenance requirements included applying a corrosion inhibitor (sodium molybdate) to the Space Shuttle Main Engine nozzles. Following the STS-127 (2009) flight, engineers observed increased nozzle corrosion instances in spite of the application of the corrosion inhibiter. A root-cause investigation found that the sponges used to apply the corrosion inhibitor contained high levels of chlorides. Apparently, the sponges being used to apply the corrosion inhibitor were themselves causing more corrosion.

It was determined that the commercial vendor for the sponges had changed their sponge fabrication process. They began adding magnesium chloride for mold prevention during their packaging process and since NASA did not have a specification requirement for the chloride level in the sponges, the sponge fabrication change initially went unnoticed. To solve this problem, NASA added a requirement that only chloride-free sponges could be used. The agency also added a specification for alternate applicator/wipes. Case closed!

NASA and the Environment—Compatibility, Safety, and Efficiency

As conscientious stewards of US taxpayers dollars, NASA has done its part to mitigate any negative impacts on the wildlife and environment that the agency's processes may impart. For NASA, it is not about technical issues; in this case, it is about the coexistence of technology, wildlife, and the environment.

Compatibility

The 56,700 hectares (140,000 acres) controlled by Kennedy Space Center (KSC) symbolize a mixture of technology and nature. Merritt Island National Wildlife Refuge was established in 1963 as an overlay of the center. The refuge consists of various habitats: coastal dunes; saltwater estuaries and marshes; freshwater impoundments; scrub, pine flatwoods; and hardwood hammocks. These areas provide habitat for more than 1,500 species of plants and animals. Hundreds of species of birds reside there year-round, with large flocks of migratory waterfowl arriving from the North and staying for the winter. Many endangered wildlife species are native to the area. Part of KSC's coastal area was classified as a national seashore by agreement between the NASA and the Department of the Interior.

Most of the terrain is covered with extensive marshes and scrub vegetation, such as saw palmettos, cabbage palm, slash pine, and oaks. Citrus groves are in abundance, framed by long rows of protective Australian pine. More than 607 hectares (1,500 acres) of citrus groves are leased to individuals who tend to the trees and harvest their fruit. Beekeepers maintain the health of the trees by collecting honey from—and maintaining—the hives of bees essential to the pollination of the citrus trees. Merritt Island National Wildlife Refuge manages the leases. Other NASA centers such as White Sands Test Facility and Wallops Flight Facility are also close to National Wildlife Refuges.

Safety

There is a limit as to what NASA can do to actually protect itself from the wildlife. During launch countdown of Space Transportation System (STS)-70 on Memorial Day 1995, the launch team discovered a pair of northern flicker woodpeckers trying to burrow a nesting hole in the spray-on foam insulation of the shuttle External Tank on Pad B. Spray-on foam insulation was comparable to the birds' usual nesting places, which include the soft wood of palm trees or dead trees. However, on reaching the aluminum skin of the tank beneath the spray-on foam insulation layer, the woodpeckers would move to a different spot on the tank and try again. In the end, there were at least 71 holes on the nose of the tank that couldn't be repaired at the pad. As a result, the stack was rolled back to the Vehicle Assembly Building for repairs to the damaged insulation.

The problem of keeping the woodpeckers from returning and continuing to do damage to the tank's spray-on foam insulation proved to be complex. The northern flicker is a protected species so the birds could not be harmed. In NASA fashion, shuttle management formed the Bird Investigation Review and Deterrent (BIRD) team to research the flicker problem and formulate a plan for keeping the birds away from the pads. After studying flicker behavior and consulting ornithologists and wildlife experts, the team devised a three-phase plan. Phase 1 of the plan consisted of an aggressive habitat management program to make the pads more unattractive to flickers and disperse the resident population of these birds. NASA removed palm trees, old telephone poles, and dead trees from the area around the pads. The agency allowed the grass around the pad to grow long to hide ants and other insects—the flickers' favorite food. Phase 2 implemented scare and deterrent tactics at the pads. NASA used plastic owls, water sprays, and "scary eye" balloons to make the area inhospitable to the birds and frighten them away without injuring them. Phase 3 involved the implementation of bird sighting response procedures. With the BIRD team plans in place and the flickers successfully relocated, STS-70 was able to launch approximately 6 weeks later.

Woodpeckers are not the only form of wildlife attracted to the External Tank. On STS-119 (2009), a bat was found clinging to Discovery's external fuel tank during countdown. Based on images and video, a wildlife expert said the small creature was a free tail bat that likely had a broken left wing and some problem with its right shoulder or wrist. Nevertheless, the bat stayed in place and was seen changing positions from time to time. The temperature never dropped below 15.6°C (60°F) at that part of the tank, and infrared cameras showed that the bat was 21°C (70°F) through launch. Analysts concluded that the bat remained with the spacecraft as it cleared the tower. This was not the first bat to land on a shuttle during a countdown. Previously, one landed on the tank during the countdown of STS-90 (1998).

Another species that NASA dealt with over the life of the Space Shuttle Program was a type of wasp called a mud dauber. Although the mud daubers aren't very aggressive and don't pose an immediate threat to people, the nests they build can pose a problem. Mud daubers tend to build nests in small openings and tubes such as test ports. This can be an annoyance in some cases, or much more serious if the nests are built in the openings for the pitot-static system (i.e., a system of pressure-sensitive instruments) of an aircraft. Nests built in these openings can affect functionality of the altimeter and airspeed indicator.

Efficiency

In keeping with imparting minimal negative impact on the environment, NASA also took proactive steps to reduce energy usage and become more "green." At KSC, NASA contracted several multimillion-dollar energy projects with Florida Power & Light Company that were third-party-financed projects. There was no out-of-pocket expense to NASA. The utility was repaid through energy savings each month. The projects included lighting retrofits; chilled water modifications for increased heating, ventilation, and air-conditioning efficiency; and controls upgrades. As an example, NASA installed a half-sized chiller in the utility annex—the facility that supplies chilled water to the Launch Complex 39 area—so as to better match generation capacity with the demand and reduce losses. The agency also retrofitted lighting and lighting controls with the latest in fluorescent lamp and ballast technology. In total, these multimillion-dollar projects saved tens of millions of kilowatt-hours and the associated greenhouse emissions.

Protecting Birds and the Shuttle

During the July 2005 launch of Discovery, a vulture impacted the shuttle's External Tank. With a vulture's average weight ranging from 1.4 to 2.3 kg (3 to 5 pounds), a strike at a critical area on the shuttle could have caused catastrophic damage to the vehicle. To address this issue, NASA formed the avian abatement team. The overall goal was to increase mission safety while dispersing the vulture population at Kennedy Space Center (KSC).

Through its research, the team attributed the large vulture population to an abundant food source—carrion (road kill). A large educational awareness effort was put into place for the KSC workforce and local visitors. This effort included determining wildlife crossing hot spots, ensuring the placement of appropriate signage on the roadways to increase traveler awareness, and timely disposal of the carrion.

NASA added new radar and video imaging systems to electronically monitor and track birds at the pads. Already proven effective, the avian radar—known as Aircraft Birdstrike Avoidance Radar—provided horizontal and vertical scanning and could monitor either launch pad for the movement of vultures. If data relayed from the avian radar indicated large birds were dangerously close to the vehicle, controllers could hold the countdown.

Endeavour, STS-100 (2001), roars into space, startling a flock of birds.

In addition to the energy-saving benefits of the projects, NASA was also able to modernize KSC infrastructure and improve facility capability. As an example, when the Vertical Assembly Building transfer aisle lighting was redesigned, better local control and energy saving fixtures were provided. At the same time, this increased light levels and color rendering capability. As another example, although KSC had a 10-megawatt emergency generator plant capable of servicing critical loads in a power outage, this same plant could not start the chillers needed for cooling these systems. As such, the backup plant was unable to sustain these loads for more than a few minutes before overheating conditions began. Soft start drives were installed on two of the five chiller motors, thus allowing the motors to be started from the generator plant and providing a true backup capability for the Launch Complex 39 area.

In yet another partnership with Florida Power & Light Company, KSC opened a 10-megawatt solar power plant on 24 hectares (60 acres) of old citrus groves. This plant could generate enough electricity for more than 1,000 homes and reduce annual carbon dioxide emissions by more than 227,000 tons. Florida Power & Light Company estimated that the 35,000 highly efficient photovoltaic panels were 50% more efficient than conventional solar panels. This solar power plant, in addition to the 1-megawatt plant, has been supplying KSC with electricity since 2009. The opening of the 10-megawatt solar field made Florida the second-largest solar-power-producing state in the country.

Summary

Throughout the shuttle era, NASA was a conscientious steward of not only the taxpayer's dollars but also of nature and the environment. Not only was the space agency aware of the dangers that wildlife could pose to the shuttle, it was also aware of the dangers that humans pose to the environment and all its inhabitants. As NASA moves forward, the agency continues to take proactive steps to assure a safe and efficient coexistence.